DESIGN & ANALYSIS OF A BICYCLE TOWING DEVICE

A Senior Project submitted

In Partial Fulfillment

of the Requirements for the Degree of

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Executive Summary

A local businessman had the idea to build a device that allows a bicycle to tow another bicycle. He built a prototype to demonstrate his idea but he wanted help in developing a product that could fit more bikes, did not require a rear rack to operate, and be manufacturable at his facility. He also expressed interest in an economic evaluation of production and marketing of the device. An analysis of customer needs led to adding reduction of weight and ease of attachment to the design requirements.

This report is about improving the original design and presents the process of developing a working prototype that provides significant improvement to the original design. It discusses research regarding patents of similar products, bike frame strength, reliability and failure testing, and manufacturing methods. The design of each prototype is modeled in Solidworks and an analysis is performed with its built-in simulation software.

The project resulted in a working prototype that allows a bicycle to tow another bicycle. The device requires no tools for installment. It uses wing head bolts to attach at the rear wheel hub, and a p-clamp to attach to the seatpost of the towing bike. The towed bike's front wheel sits on a bar with hooked ends and the top of the wheel is tied to the device. It doesn't require a luggage rack on the towing bike.

We also included a description of the manufacturing methods and processing required to manufacture this device. The cost of the final design consists of material and labor costs. A facility layout is discussed with regard to production capacity.

Acknowledgements

We would like to thank our client Rod Hoadley for coming up with this project, our advisor Dr. Daniel Waldorf, Dr. Liz Schlemer, and those that helped us build our prototypes: Adam, Kyle, and Mason.

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1.0 Introduction


Figure 1: Prototype

This report details the design process and manufacturing considerations of creating a device that will allow a bicyclist to tow a riderless bicycle behind their own in a safe and effective manner.

The idea for this project came from Rod Hoadley, a professor in the Industrial & Manufacturing Engineering department at Cal Poly. Additionally, Mr. Hoadley owns a bike rack manufacturing company and facility in San Luis Obispo. He created a prototype for his own personal use that allows his bicycle to tow another bicycle. It is built with solid cold-rolled steel cylindrical bar stock, gear ties, and hose clamps, and it attaches to the left chain stay and the luggage rack (See Figure 1). Mr. Hoadley has the economic means to manufacture this device to scale, but currently there are problems with its design and functionality. Several of these problems are listed below:

- Attachment is at a potentially weak point on the bicycle
- The weight of the device is undesirably heavy
- Tools are required for attaching and detaching
- Fasteners are non-standard and foster inconsistent fastening
- Operational errors exist: Turning can be impeded or the towed bicycle falls over
- A luggage rack is required for attachment

This project will focus on improving his product idea, potentially solving the specified problems, and also investigating the manufacturability and financial justification of producing and selling this device. Not only do the customer requirements need to be met, but the device needs to be reliable and mechanically sound. In order to achieve these desired results the current design will first be modified and analyzed.

The project scope can be defined in four categories:

- Final design/prototype: This will not only include a design but an analysis on the strength/reliability of the device, product structure, and safety. The design will meet the goals of adjustability (fits on variations of the diamond frame), detachability (without tools), and non-bulkiness (minimize shipping volume where possible).

- Market analysis and customer specifications: Analyzing what the customer would demand for this product (QFD), and how that would affect investment profitability (customer needs versus limitations of the design, especially adjustability).
- Manufacturing feasibility: Analyzing the manufacturing and assembly processes (i.e. welding) and constraints in producing this product.
- Economic justification: Analyzing the economic value of producing the product (price per unit vs. manufacturing volume).

This problem will be approached with an analysis of the current state. The tests that will be performed are a static Finite Elements Analysis via simulation tests on SolidWorks and a Failure Modes and Effects Analysis. Then new designs will be generated and tested with the same methods, including other tools such as Quality Functional Deployment. Final design(s) will have a prototype built and field tested. For manufacturing feasibility, the steps of the manufacturing process will be outlined, the cost of materials and labor will be determined, and from that the cost of manufacturing this product (given different mfg. volumes) will be derived. Although, some of our research comes from patents, the final design for this paper will not be patented.

It is important to note that dynamic or vibration tests will not be considered in the scope of this project, nor will material or member structure considerations be considered, due to the limitations of our mechanical expertise and our focus on industrial engineering concepts. These considerations along with reliability and failure testing will need to be addressed if our project is developed into the future.

The next sections cover the background of the project, some patents of similar products, and various research topics. Then a discussion of the original design, proposed designs, and the methodology we used to test them. Finally, this report will end with the results and conclusion.

2.0 Background and Literature Review

This section discusses the information gathered prior to and during the design process.

2.1 Background

This type of bike-tow design has been tried before in various forms. We have found four patents for bike-towing devices and one patent for a single track trailer hitched to a bike. The advantages or limitations of these designs are unclear, we just know that a commercial bike-tow product, if available, isn't widely sold. Our goal, in a sense, is to offer our design as a candidate for commercialization and at the same time meet the needs of our client.

The following research is grouped into four categories described below.

2.2 Literature Review

This literature review starts with a walkthrough of some existing patents. The purpose of this research is to investigate what types of designs other projects have created in the past in order to provide a basis for developing new designs. Next, a review on bike frame strength is presented. The purpose of this research is to determine which parts of a bike frame are suitable for application of loads. A review of reliability and failure tests was done in order to determine what type of tests can be applied to this project. Lastly, research was done on manufacturing methods. This research will be used in considering different ways to produce the bike tow device.

2.2.1 Similar Product Patents

The patent by Giese for a bicycle towing device was issued in 2007, and serves the purpose of towing a vacant bicycle behind the front bicycle or coupling two bicycles together for a potential purpose of teaching a child how to ride a bicycle. This patent explains that other attempts at creating a successful bicycle towing device usually fall short by providing too flexible of a connection between the two bikes, allowing the trailing bike to steer on its own. In contrast, too rigid of a device can misalign the wheels of the two bikes, resulting in the front tire of the back wheel lifting of the ground during some maneuvers. This device connects its arm to the seat post of the leading bike, which gives the structure the most stability. The arm only allows only for pivoting in one axis-downwards or upwards, to account for height differences in the two bicycles.

Paola Peruzzo (2012) invented a device that consists of a towing arm, and a connector. The connector joins the towing bike and the towing arm and it attaches to the towing bike's seat post. The towed bike is attached at both sides of its front axle as well as the head tube. While in tow, the towed bike's front wheel is suspended off the ground. The towing arm allows for rotation about a vertical axis and a horizontal axis perpendicular to the direction of travel.

France Couture (1998) invented a device similar to Peruzzo's. The difference is that Couture's device requires detachment of the towed bike's front wheel. The wheel is then attached on the top of the towing arm.

Lyle R. Hilk (2002) invented a trailer that allows you to carry luggage behind a bicycle. The trailer has one wheel and is attached by both sides of the rear axle of the towing bike. The attachment at the rear axle tows for rotation about a horizontal axis perpendicular to the direction of travel. The arm connecting the trailer to the rear axis is connected to the trailer by a vertical hinge, which allows for rotation about a vertical axis. The design of the connection arm could be useful for our application.

A paper by Richard Klein on Engineering Education outlines several unfeasible designs for a stable single track trailer, i.e. a "towed riderless bicycle which will follow, steer, and balance of its own accord behind a lead bicycle", and one feasible design. The purpose of the paper is to discuss hands on projects for engineering education but it also provides a good overview of the designs themselves. While our project is not to design a self-steering, self-balancing bicycle, this paper offers insight into design challenges and issues (Klein 1991).

2.2.2 Bicycle Frame

Experimental results, from a study by Zhongxia et al, show that loads on a bicycle frame and load distribution are different under different riding conditions. The simulations results state that the force on a seat pillar can vary between 170 and 300 N, the force on a head tube can vary between 213 and 487 N, the force on a bottom bracket can vary between 300 and 488 N, and the force can vary greatly with cycling speed. It also notes that "stress and its distribution on frame are apparently different when the frame is loaded according to the bicycle testing standard and the simulation experiment in this paper respectively" (Zhongxia et al 2011).

A study on bicycle structural dynamics by Champoux et al, did testing on how a bike frame reacts to bumps in the road, among other things. They found that an impact with a raised bump can cause the front wheel to experience over 800 N of force and the rear wheel can experience over 1000 N of force. The paper also discussed the ability to predict the fatigue life of metal weld joints using a "hot-spot" technique where the stress level of the tube is measured "at two specific locations near the weld." Those data points are then "used to extrapolate a stress level at the root of the weld joint" (Champoux et al 2007).

A basic Finite Element Analysis is carried out in a paper by Pazare and Khamankar found that the seatstays absorb most of the forces a bicycle experiences due to static startup, constant pedaling, and vertical impact (Pazare and Khamankar 2014).

The Oxtail bike trailer company notes that there are several principles of towing that can be applied to bicycles. First, a trailers weight should be distributed onto the towing bicycle. Second, the if the hitch is in front of the bicycle's rear axle it decreases the chance it will experience a “force that can cause an articulated vehicle to jackknife.” Third, a lower center of gravity will contribute to the stability of the vehicle system.

2.2.3 Reliability and Failure Testing

The crucial importance of incorporating fatigue analysis into the engineering design stage was discussed by Fatemi et al. largely due to the fact that mechanical failures are drastically costly. For example, the resulting costs of mechanical failures in 1978 was estimated at 4% of the Gross National Product. Safety factors also have a strong relationship with fatigue analysis. Overstated factors could result in unfitting or too expensive products, whereas understated factors could result in preventable failures. It is important to consider appropriate safety factors, but they shouldn’t be the sole reliance (Fatemi et al. 2000).

While taking reliability into consideration during the beginning stages of the design process can appear like a costly and unnecessary use of resources, According to O’Connor, it is an essential step in modern-day product design. Preventative measures are far less costly than addressing issues as they reveal themselves down the line. To ensure an effective approach in designing for reliability (DfR) the process should follow the steps below:

1. Identify
2. Design
3. Analyze
4. Verify
5. Validate
6. Control

The identify phase involves the establishment of the system reliability requirements--identifying the minimum time or usage that the product is intended to function for. Several tools and techniques, such as Quality Functional Deployment (QFD), competition benchmarking, and usage distribution are implemented in this stage.

The design phase highlights the use of a Failure Modes and Effects Analysis (FMEA) for identifying all potential failures, their likelihood, and the resulting consequences. This tool should be first used in this stage, but should be repeated and reanalyzed several times in the design process. Its main purpose is to help in identifying and prioritizing the critical components in the design. It is also notable that this analysis can vary depending upon the designated viewpoint--safety or cost for example. These different viewpoints can provide beneficial results as long as distinctions are stated.

A common scale used for quantifying risk priority numbers (RPN) in an FMEA includes the following:

- Severity: 1-10 with 10 being the most severe and 1 being the least severe

- Occurrance: 1-10 with 10 being the most likely to occur and 1 being the least likely to occur
- Detection: 1-10 with 1 being the highest chance of detection and 10 being the lowest chance of detection

The validation phase incorporates different testing methods to confirm predictions and analysis about the functionality and reliability qualities of the product. A successful validation phase will resolve design and manufacturing concerns that may have been improperly analyzed or ignored.

O'Connor highlights that DfR cannot always predict all modes of failure, but a well-implemented DfR can help achieve a reliable design while simultaneously reducing the cost and time of reliability testing. A thorough reliability test program should encompass the following components:

- Functional testing: verifying that the simple performance requirements are satisfied
- Environmental testing: verifying that the product functions correctly under its intended range of environments
- Statistical tests
- Reliability testing: verifying that failures will not occur under expected loads and lifetime
- Safety testing

An effective plan for this testing program should include distinctions between the components and subassemblies to be tested, requirements for testing--such as testing equipment--and a standardized reporting system for the testing. The number of items to test will generally be no fewer than four items, where the number depends on the complexity and cost of producing test items. Statistical tools can help to determine a meaningful number of components to test. (O'Connor 1994)

Several different types of testing equipment are available for testing the fatigue of parts in tension, torsion, or flexing. This testing procedure involves the application of a repeated stress to the part and a documentation of the number of cycles until failure. After this is repeated several times with different stresses, a plot of stress vs. number of cycles can be created. Ferrous metals, like steel, will display a stress curve that levels off at the part's fatigue limit. This level of stress is associated with an infinite life for this part. This process can be very useful in calculating a safe lifetime for a part under certain loading. This testing method is not always recommended as it requires several time consuming trials to obtain notable data, and many factors affect the fatigue of a part which may not be representative in a laboratory testing environment. Particularly surface finish, corrosion, and temperature are additional factors for consideration of fatigue. (Marlow 2002)

2.2.4 Manufacturing Methods and Considerations

This section discusses different aspects of welding and powder coating in the context of this project.

2.2.4.1 Welding

Types of Welding:

Shielded Metal Arc Welding (SMAW):

A high electric current is fed through a consumable stick electrode covered in flux that melts to the metal pieces that are being joined. One of the easiest methods to learn. Good for structural applications.

Gas Metal Arc Welding (GMAW/MIG):

Uses a weld gun to feed weld metal onto the material you are welding together. A high current melts the weld metal to the workpiece, protected from the elements by an inert gas. One of the fastest welding methods. Most widely used method.

Flux Cored Arc Welding (FCAW):

Uses a weld gun to feed an electrode with a flux core onto the material you are welding together. A high current melts the weld metal to the workpiece, protected from the elements by the flux and slag created.One of the fastest welding methods.

Gas Tungsten Arc Gas Welding (GTAW/TIG):

An arc welding process that uses a non-consumable tungsten electrode and a consumable filler metal rod. Good for metals that don't contain much iron. Complex and time-consuming welding method. Produces strong welds when done properly.

This paper by Lee et al. investigates fatigue properties of different welding methods on dual phase steel—a common material used in automotive parts such as frames or wheels. Laser welding, tungsten inert gas (TIG) welding, and metal active gas (MAG) welding are compared on how they affect the hardness of the weld metal and the heat affected zone. The concern is the impact of these soft heat-affected zones leading to deterioration of the weld location over time. The paper concluded that TIG and laser welding both performed better than MAG welding in terms of yield strength and fatigue. However, resistance to fatigue was expectedly worse for all welding methods compared to the non-welded material. (Lee 2014)

While some welding faults can be attributed to the skill and knowledge of the welder, or lack thereof, other factors can affect the quality of the welds. As a result, consistent inspection and testing of the welds is necessary in a manufacturing environment. A visual inspection by an experienced welder during welding and after the process is beneficial in estimating the strength of the weld, but can sometimes be unhelpful due to the orientation of the weld.

This source discusses a plethora of non-destructive testing methods for gaining insight into the strength of the weld. Magnetic tests will reveal cracks in the weld due to the indication of a current change caused by a change in magnetic flux. X-ray methods operate by evaluating the proportion of of x-rays that get absorbed by the welded material. Thicker and denser materials will allow less rays to pass than less-dense materials. The welded material is placed in front of film in which x-rays are projected on to. Denser areas in the material will display lighter shading on the film because less rays get through and defects will be darker on the film. This method involves a power supply that heats a filament to release electrons and x-rays, and thus requires a cooling system to prevent the anode from overheating. Using gamma rays instead of x-rays is advantageous in that no power supply or cooling method is needed. However, the resulting film used to interpret the density and thickness of the weld has less contrast and is therefore more difficult to decipher. Additionally, proper handling methods of these radioactive sources must be considered, and the radioactive content of the source cannot be adjusted and its depreciation may prevent the method from being used. Ultrasonic testing involves the projection of high frequency waves onto the welded area. Defects in the weld will emit different types of echoes, from which an estimation of the type of flaw can be gathered.

There are of course tradeoffs between using destructive and non-destructive testing methods on welded parts. Destructive tests provide the most information about the weld quality and strength, however due to the nature of their destructiveness they have a limit to their use.

In regards to destructive weld testing, the most fundamental application of this in a workshop space is a nick break test. This involves hammering the welded area to break open the part at its weld location. Often small "nicks" using a saw are applied to the ends of the weld, ensuring that the part will break at the weld point. This method is very useful for highlighting errors in amateur welding environments but becomes insignificant in more advanced welding shops. Additionally, bending the welded part in a vice may reveal cracks which indicates a lack of ductility. More advanced destructive tests can usually not be completed in a workshop and require significantly more time. Both microscopic and macroscopic assessment of the weld joint requires a cross section of welded area to be both polished and etched in preparation for examination. The crystal structure of the weld under a microscope can reveal similarities to that of the parent metal which will illustrate an idea of the strength of the weld. Macroscopic observation is of course not as detailed but it does provide valuable indications of cracks, gas holes, and the overall coarse structure. Corrosive tests can be useful for predicting the behavior of welds when exposed to their expected environment. Concentrated solutions can simulate years of corrosive exposure in a matter of several days. Several mechanical tests can be performed using testing machinery and properly prepared testing parts. Parts often need to be cut to proper size or machined to uniform size before performing tests such as tensile, torsion, impact, or hardness. A notable fatigue test is the Haigh test which involves vibrating push-pull forces that are much less than the material's maximum tensile or compressive strength. These tests are often very time consuming but can adequately simulate environments involving repetitive force variation--particularly a bicycle. (Davies 1994)

2.2.4.2 Powder Coating

This source sets the stage for details about powder coating by first explaining the benefits of using dry powder coatings compared to liquids, such as paints. Powder tends to be more environmentally friendly whereas liquid solvents are correlated with air pollution. Solvents also pose a fire risk due to their flammable nature and no mixing or viscosity considerations are needed with dry powder. Additionally, a more friendly learning curve is present in powder coating and cleanup can be accomplished simply with compressed air. The book also stresses economic advantages from initial equipment investment savings and fuel savings. Overall, powder coating requires only one coat, less bake time, and the ability to recycle oversprayed material. Ultimately labor savings are a large part in the choice between liquid coatings and powder.

The fundamentals of a powder coating operation are as follows:

- Metal parts need to be preheated in an oven to a temperature above the melting point of the powder that will be applied. This ensures that the powder adheres to the metal when it is sprayed on.
- Powder is distributed on to the metal parts, often with a handheld gun. This spraying operation takes place in an enclosure that allows a machine system to recover excess powder that doesn't meet its target during the spray.
- Finally, parts pass through a curing oven which ensures the powder coat is uniform in distribution.

The fluidized bed powder coating method incorporates preheating and curing into the process but the actual fusion of the metal and dry powder occurs by lowering the metal parts into a tank full of circulating powder. The time that the part stays in the tank and the temperature of the metal part both affect the coating thickness.

Since there is a desire to waste as little powder as possible and for the powder to adhere to the part as best as possible, the process of electrostatically charging the powder is common in the industry. Known as ion bombardment, powder particles become charged upon leaving the spray gun due to the high voltage that is applied to an electrode near the exit point of the gun. Air particles near this point become charged which in turn charge the powder particles as they both collide due to the powder being forced out of the gun at high pressure. Pre-heating parts before the spray step is optional as powder will adhere to the surface regardless of the temperature of the part. However, depending on the desired coating thickness heating may be necessary. Without heat, particles will stop adhering to the surface after a certain thickness has been achieved. The spraying time predictably has a positive relationship with the coating thickness, but this relationship is also dependent on the charge voltage, the spray distance, the powder output, and the powder particle size. Using an average charge voltage of 54 KV, an average spray distance of 5", a powder output of 0.5 g/sec, and a particle size of 12 μ, it would take roughly between 5-10 seconds to powder coat one part with a film thickness of 4 mils.

Since the bondage of the powder to the part is so vital for this operation, preparation for this step becomes very important to ensure proper bondage is reached. In general, removing oils and dirt, creating an adequate part finish, and applying any chemicals to aid in corrosion resistance, may all be necessary before a part is ready to be powder coated. (Miller 1974)

3.0 Design

This section will cover the requirements of the design, an analysis of the initial design, and a "voice of the customer" analysis. Then each prototype, the rationale of their design, and their limitations will be discussed.

The design requirements are:
- Manufacturable at Mr. Hoadley's factory
- Fits most diamond frame bicycles (may require adjustable design)
- Attachment doesn't require a luggage rack
- Safe to operate

The user specifications are:
- Weight and volume reduction from current design
- Easy to attach and detach
- Low cost to produce

To meet these requirements the current state design will be analyzed to discover what is lacking and new designs will be drafted to fill those needs. The current state design is an assembly of solid steel bars quickly put together in order to test the feasibility of this type of device.

All of the part drawings and simulation were done in Solidworks and Solidworks Simulation Xpress. Different materials are not fully considered for this project, but are discussed later in this chapter.

3.1 Initial State Solidworks Model and FEA

The following solidworks model drawing was created to analyze the mechanical properties of the current working prototype and serve as a baseline for future designs.

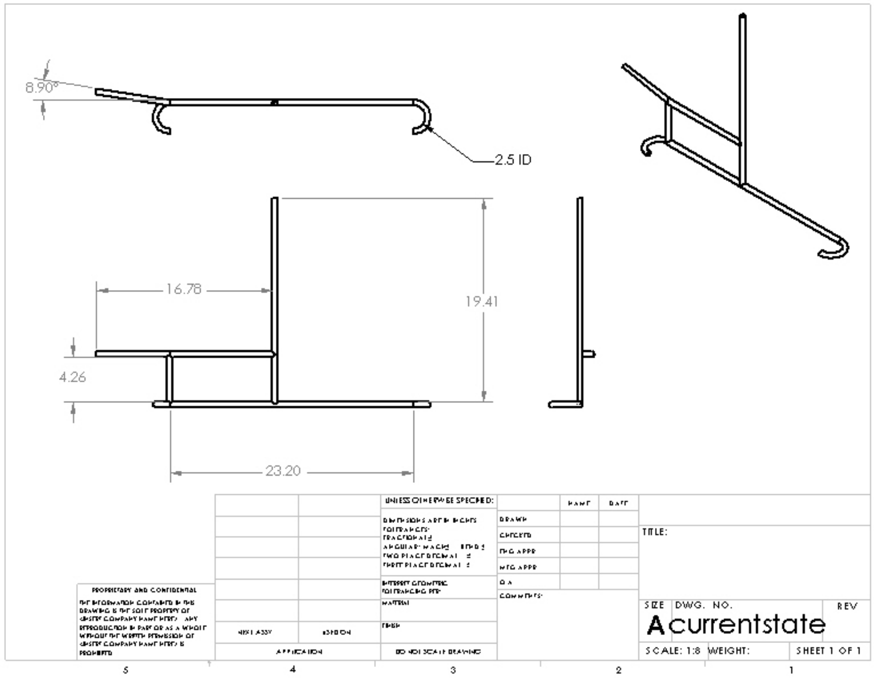


Figure 2: Solidworks drawing of Prototype

This deflection test was done using a 88 Newton (20 pound) force that was distributed across two points at either end of the bar that holds the towed bike (the image only shows one). That number was chosen to represent a heavy bicycle or a worst case scenario. The largest deflection is 3.6 mm at the rear-most hook. This design is fairly rigid because it is secured close to the frame. The smallest factor of safety in this simulation is 3.8.

All of the simulations assume the material of the device is 1020 colled rolled steel. This is the material that was used in prototyping. Solid round rods of varying diameter were used for prototyping because that is what the client uses at his facility. A further discussion of materials and member geometry is at the end of this chapter.

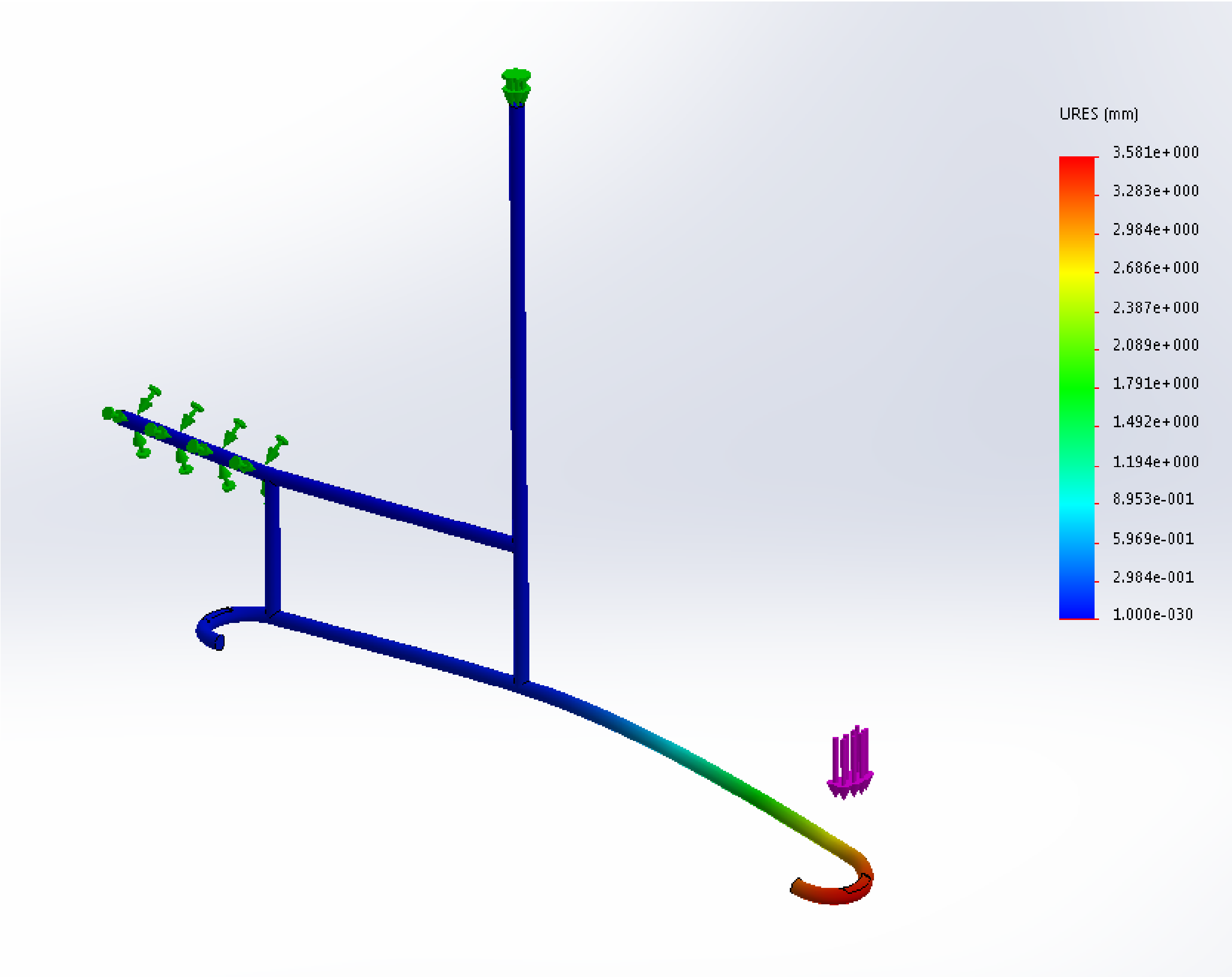


Figure 3: FEA of Prototype

3.2 Failure Modes & Effects Analysis

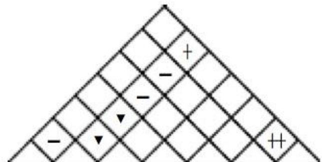
The FMEA shown in *Figure 3* identifies potential and previously observed failures with the current device and prioritizes where focus should be directed as the design evolves. These failures range from the most severe--fracture of a component on the leading bicycle--to minor instances, such as the towed bike falling over when moving backwards. While the minor instances do not result in very severe consequences, the likelihood of them occurring and the probability of detection result in larger risk priority numbers (RPN).

Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrance	Current Process Controls Prevention	Current Process Controls Detection	Detection	RPN	Recommended Action
Leading bicycle can fracture	Injury of rider, damage to leading bicycle, damage to trailing bicycle, damage to towing device	10	Load exeeds strength of leading bike frame	2			1	20	
Device can fail	Serious damage to towing device, damage to trailing bicycle	8	Load exeeds strength of device	1			2	16	
Device can fail	Serious damage to towing device, damage to trailing bicycle	8	Corrosion weakens device, load exceeds strength	1			2	16	
Device fastener can fail	Damage to towing device, damage to trailing bicycle	7	Improper attachment, fastener fracture	3			2	42	
Left turn impeded	Bike accident	4	Yoo sharp turn, trailing front tire too close to the ground	5			3	60	
Trailing bicycle falls when backing up	Motion halted, bike scratched	2	Not careful when backing up, design flaws	5			4	40	

Figure 4: Failure Modes and Effect Analysis for Initial Design

Indicated by the FMEA, a main focus of a future design will be attempting to fix the minor, yet common, operational errors that exist in the current model. This does not exclude the other failure modes from consideration. Any failures in the device itself, the fasteners, or the bicycle frame itself will be hopefully prevented through analysis of reliability and material properties of the product. This analysis will be performed after each prototype to see if the RPN value has improved and been reduced, and to see if new potential failure modes have developed.

3.3 Quality Functional Deployment



Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality	Tool-less fasteners	Weight	Adjustable length of connection arms	Adjustable attachment to towed bike	Meets regulations	Allows for a luggage rack	Needs a luggage rack	Rod's design	Prototype 1	Prototype 2	Prototype 3	0	1	2	3	4	5
				Column #	1	2	3	4	5	6	7	Competitive Analysis									
				Direction of Improvement:	▲	▼	▲	▲	x	x	x										
1	9	17.8%	8	Easy to attach to towing bike	Θ	▲	▲				O	2	4	3	4						
2	9	13.3%	6	Easy to operate		▲		Θ				3	0	0	4						
3	9	22.2%	10	Safe to operate	▲	O	O	O	Θ			2	0	0	4						
4	9	11.1%	5	Fits all bikes			Θ	Θ		O	Θ	1	4	4	4						
5	3	4.4%	2	Does not take up much space when detached			O	▲				4	2	3	2						
6	9	8.9%	4	Does not interfere with luggage rack			O			Θ	Θ	5	0	5	0						
7	1	11.1%	5	Reliable	▲		▲	▲				4	2	4	5						
8	3	11.1%	5	Inexpensive	▲	O	O	O	▲			2	3	4	2						
				Target or Limit Value	none	none	none	none	none	none	none										
				Difficulty	5	3	8	10	2	6	3										
				Max Relationship Value in Column	9	3	9	9	9	9	9										
				Weight / Importance	204.4	131.1	268.9	335.6	211.1	113.3	233.3										
				Relative Weight	13.6%	8.8%	18%	22.4%	14.1%	7.6%	15.6%										

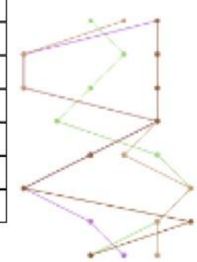


Figure 5: House of Quality

This QFD compares the relationship between customer wants and product features, and compares the initial design along with the two prototypes against the customer wants. The most important features were the adjustability features that would increase the number of bikes that fit with the device. These features also are difficult to design and manufacture, and would most likely be considerations made after a fixed (non-adjustable) design was found.

3.4 Prototype 1

This section discusses the justification of the design decisions made for Prototype 1, the part model, an FEA, and the limitations of the design.

3.4.1 Explanation of the Design

The first priority for a new design was to eliminate the need for a luggage rack to use the device. This was accomplished by designing the device to straddle the leading bike's rear wheel and securing the device to the seat post. The towed bike's front tire would be suspended above and to one side of the lead bike's rear tire. An added benefit of this design is that the towed bike's front tire won't scrape along the ground. A limitation is that the lead bike can't have a luggage rack to operate the bike-tow device. To reduce weight a ⅜ in. diameter steel bar stock was used, as opposed to the ½ in. diameter steel used for the initial design; this prototype ended up being about a pound lighter (3.3 lbs. compared to 4.1 lbs.) because of its thinner design. If the initial design was made with ⅜ in. diameter steel it would weigh 2.3 lbs. To achieve a toolless attachment the device is fastened to the lead bike with three P-clamps. The ends of the steel bar are hammered flat and have a holed drilled into them. A bolt is fitted through the hole of the device and the holes of the P-clamp then secured with a wingnut.

3.4.2 Prototype 1 Solidworks Model

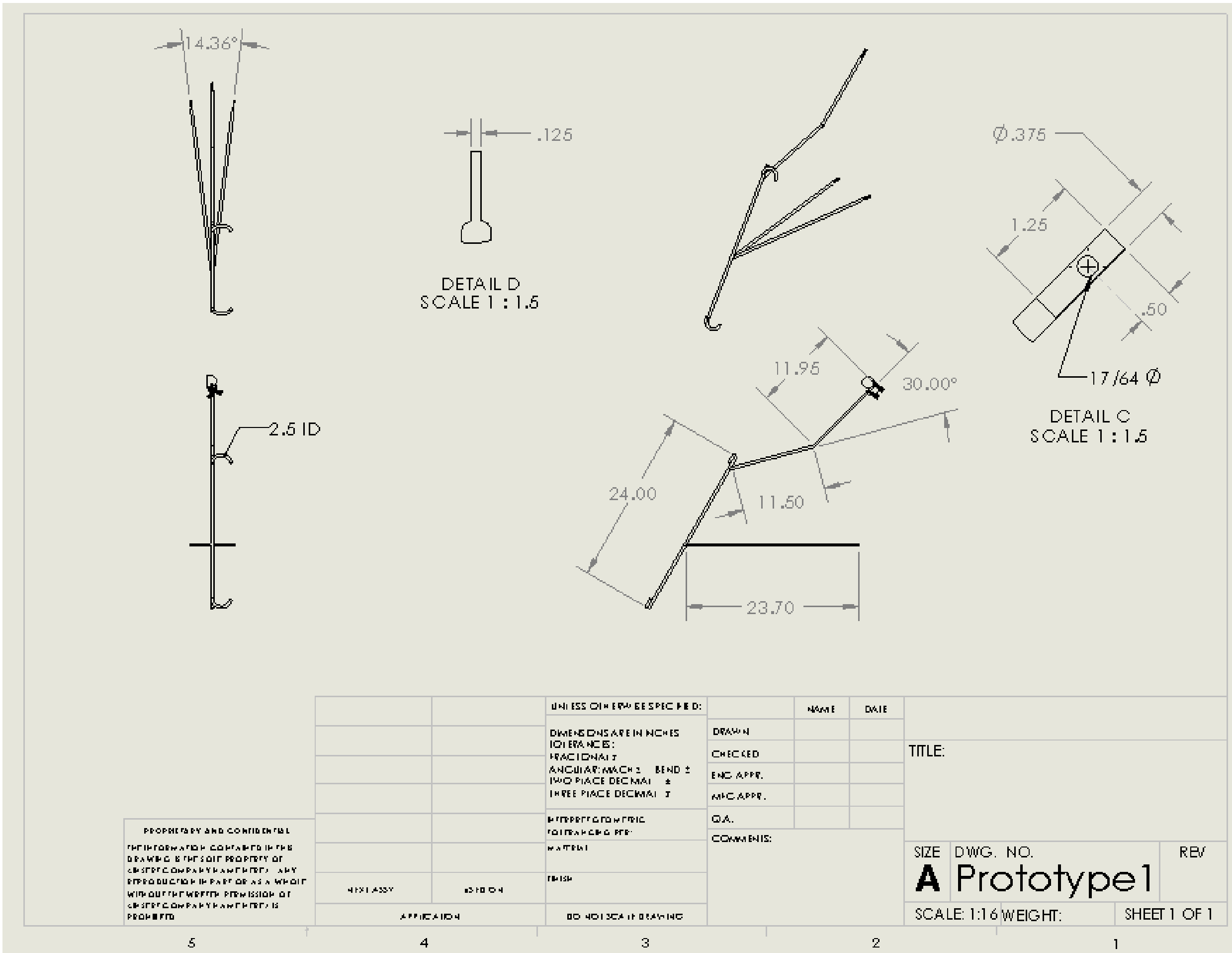


Figure 6: Solidworks drawing of Prototype 1

3.4.3 Prototype 1 Finite Element Analysis

This deflection test was done using a 88 Newton (20 pound) force that was distributed across two points at either end of the bar that holds the towed bike.The largest deflection is 5.0 mm at the rear-most hook. This design is fairly rigid because it is secured on both sides of the rear wheel. The smallest factor of safety in this simulation is 2.4.

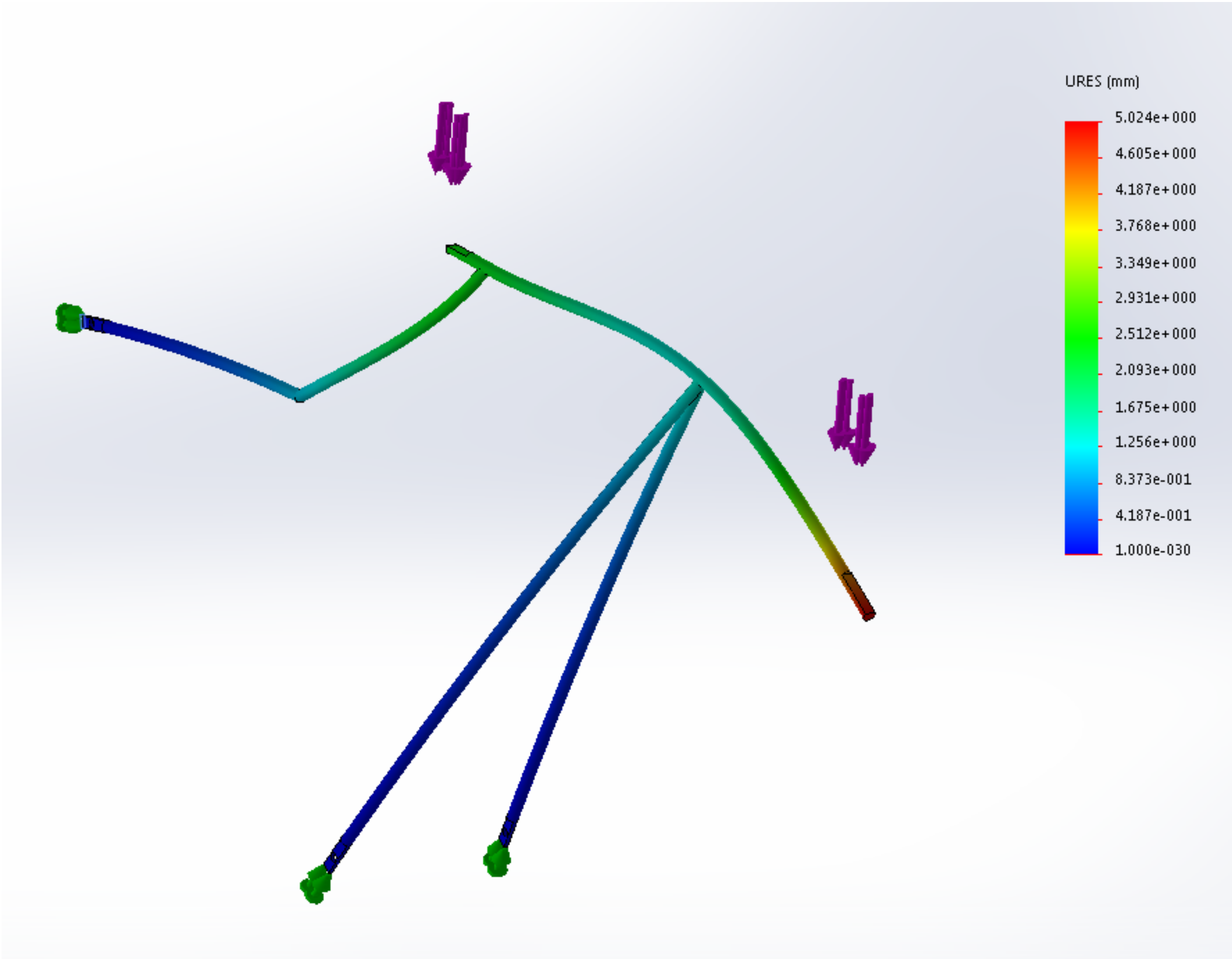


Figure 7: FEA of Prototype 1

3.4.4 Limitations of the Prototype 1 Design

Prototype 1 attached very well to the towing bike. However, it didn't stop the front wheel of the towed bike from falling to the side. This was avoided by tying the wheel down against one of the stay attachment rods. With the front wheel secured, the towed bike's fork fell backwards causing the bike to fold and fall when the towing bike turned. This is a similar failure to what was seen when the initial state model was rolled backwards.

3.4.5 Fasteners in Prototype 1

Research into how some bicycle users install a rear luggage rack onto their bicycle without the option of fastening holes near the rear hub, led us to the discovery of the P-clamp. This part is useful in attaching to the seatpost or seatstays--any round bar--and connecting to a bolt. Since toolless fastening and adaptability to different bicycles were desired in our design, P-clamps were utilized.

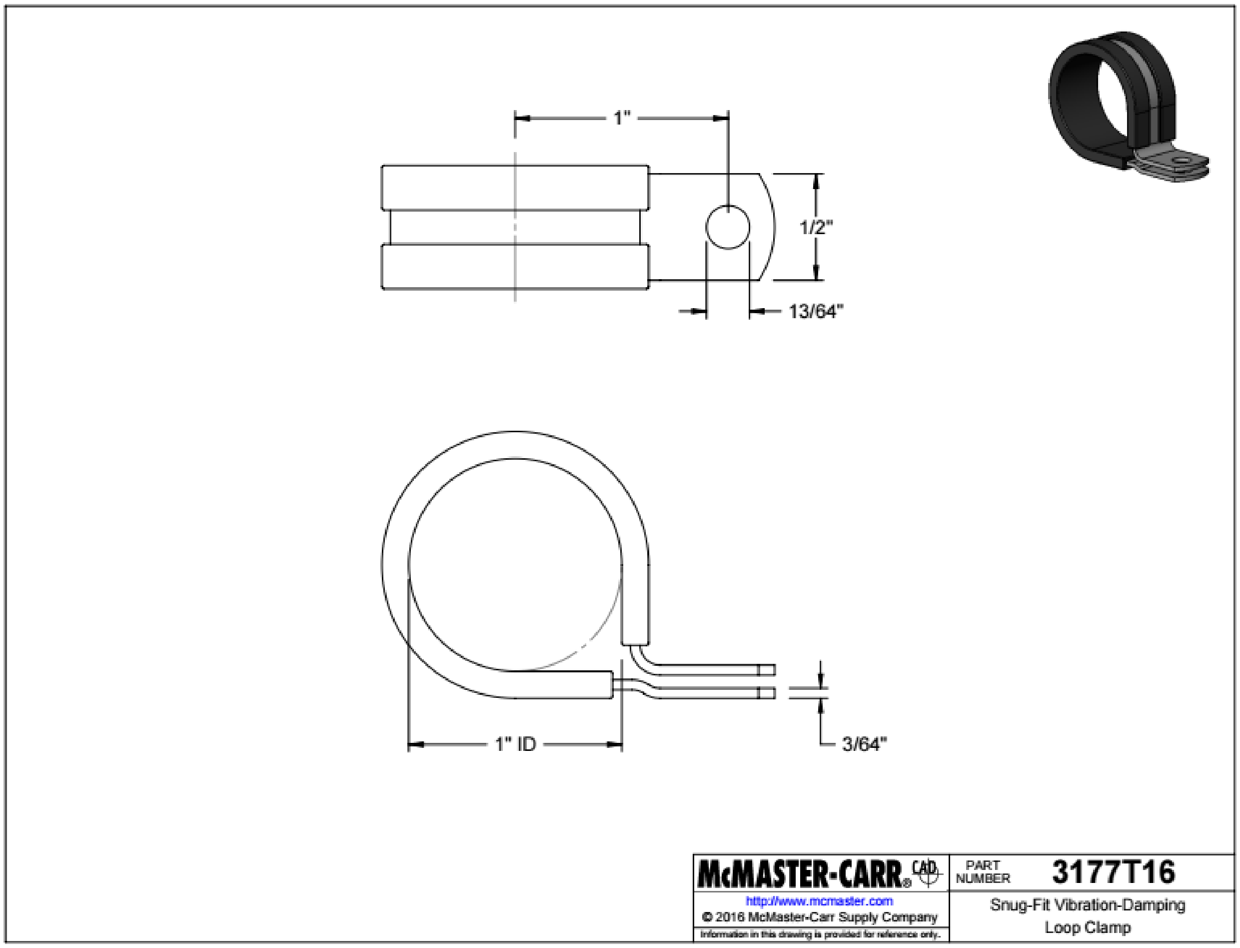


Figure 8: Drawing of a 1” P-clamp

3.5 Prototype 2

This section discusses the justification of the design decisions made for Prototype 2, the part model, an FEA, and the limitations of the design.

3.5.1 Explanation of the Design

This design was intended to resolve the stability problem of the first design and to eliminate the need for a luggage rack as in the first prototype. This was accomplished by designing the device to attach to the chainstay like the initial design but to secure the device by extending a connector rod up to the seat post. The towed bike’s front tire would sit slightly higher off the ground than in the initial design and would be secured by a vertical bar coming off the device. A benefit of this design is that it could be used whether or not the lead bike had a luggage rack. Again, to reduce weight a ⅜ in. diameter steel bar stock was used, this prototype ended up being about a pound lighter than the initial design (3.0 lbs. compared to 4.1 lbs.) because of its thinner design. To achieve a toolless design the device is fastened to the lead bike with a P-clamp and two hose clamps. As in the last prototype the ends of the steel bars are hammered flat and have a hole drilled into them. A bolt is fitted through the hole on the device and the holes of the P-clamp then secured with a wingnut. The hose clamps are used to fasten the device to the left hand chainstay of the lead bike near the front hook and an inch from the end of the connecting rod.

3.5.2 Prototype 2 Solidworks Model

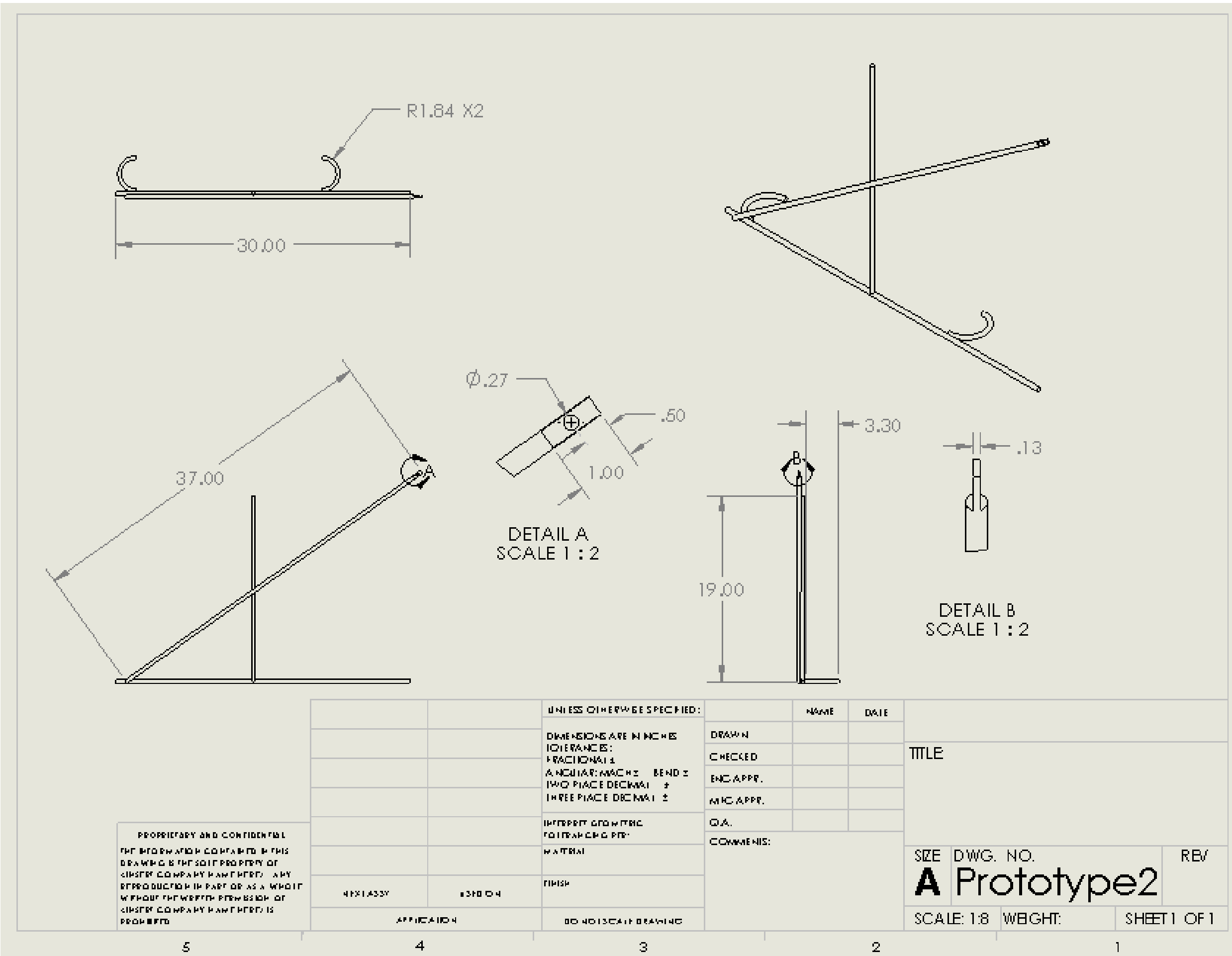


Figure 9: Solidworks drawing of Prototype 2

3.5.3 Prototype 2 Finite Element Analysis

This deflection test was done using a 88 Newton (20 pound) force that was distributed across two points at either end of the bar that holds the towed bike. The largest deflection is 1.3 mm at the rear-most hook. The smallest factor of safety in this simulation is 4.3. This design is fairly rigid against a downward force but not a sideways one. The sideways simulation used a 10 pound force applied where the top of the front wheel of the towed bike would be pressing against the device. The largest deflection is 21 mm at the top of the vertical bar. The factor of safety in the sideways simulation is 0.53.

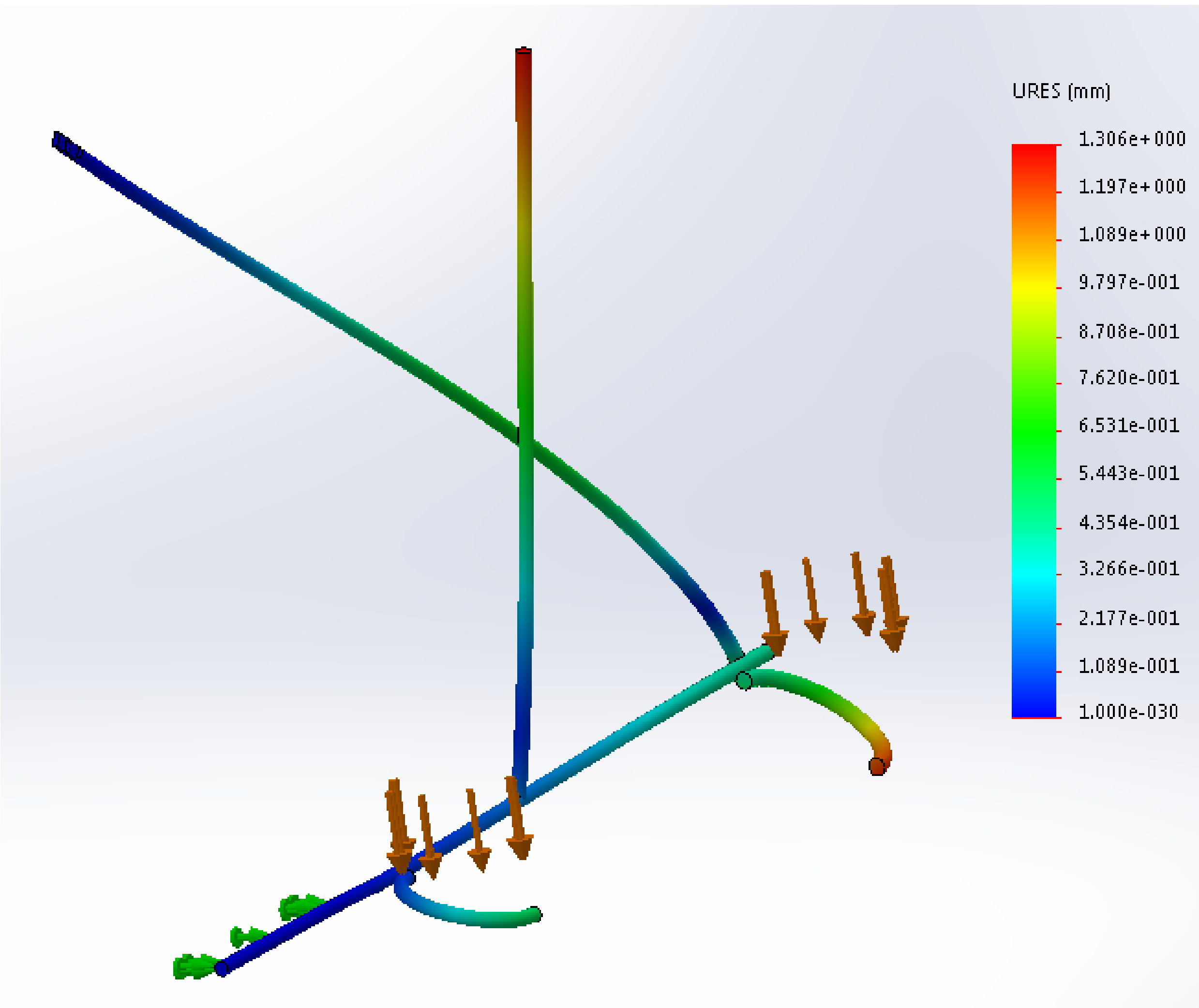


Figure 10: FEA of Prototype 2

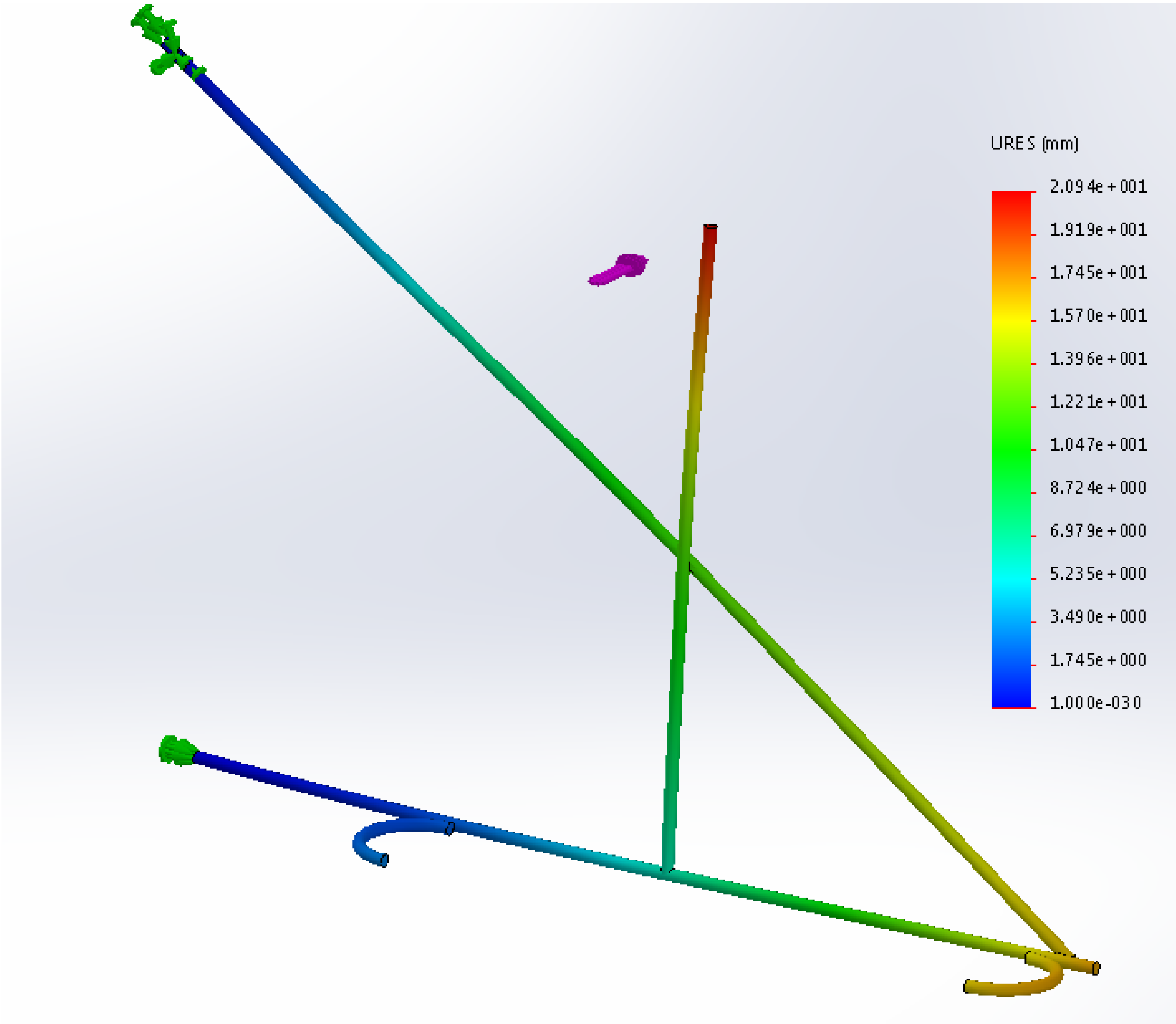


Figure 11: FEA of Prototype 2 (horizontal force)

3.5.4 Limitations of the Prototype 2 Design

Prototype 2 attached well to the towing bike but it flexed and touched the back tire after the towed bike was mounted. This made it impossible to operate since it didn't allow the wheel to turn. The flex is partially caused by the rods being fairly thin. The initial state used ½ in. diameter rods, and prototype 2 used ⅜ in. diameter.

3.6 Prototype 3

This section discusses the justification of the design decisions made for Prototype 3, the part model, and an FEA.

3.6.1 Explanation of the Design

This design was intended to solve the problem of the device stopping the rear wheel of the towing bike to turn. This was accomplished by fastening the device on both sides of the rear axle hub and using ½ in steel bars. Three ends are hammered flat and have holes drilled into them. Two are attached using the threaded eyelets. The last end is attached to the seatpost with a P-clamp. The hook bar is suspended below the hub in order to lower the center of gravity. Because of the extra steel needed to mount the device on both sides of the axle this design weighs 6.6 lbs, which is significantly heavier than any of its predecessors (initial state: 4.1 lbs).

3.6.2 Prototype 3 Solidworks Model

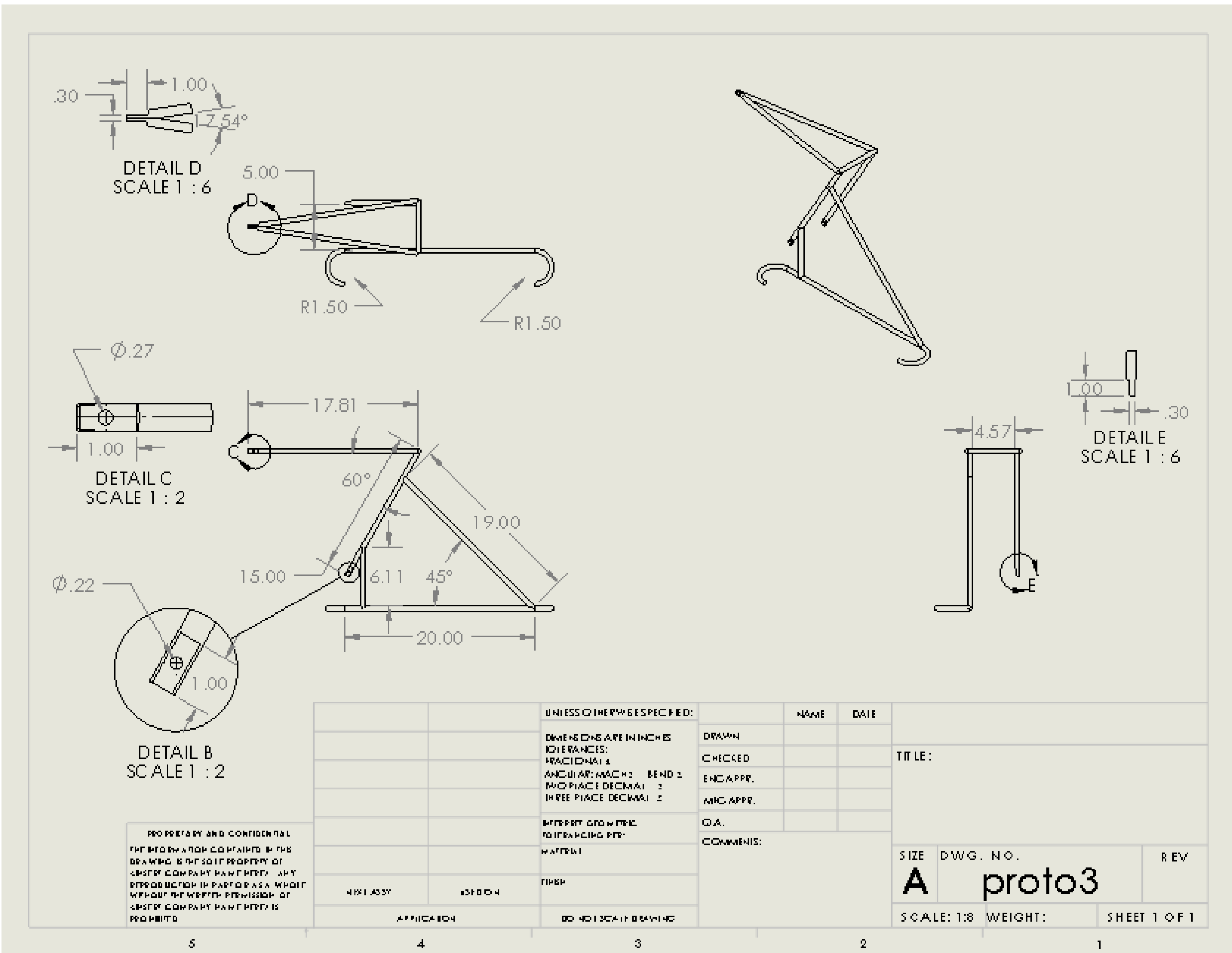
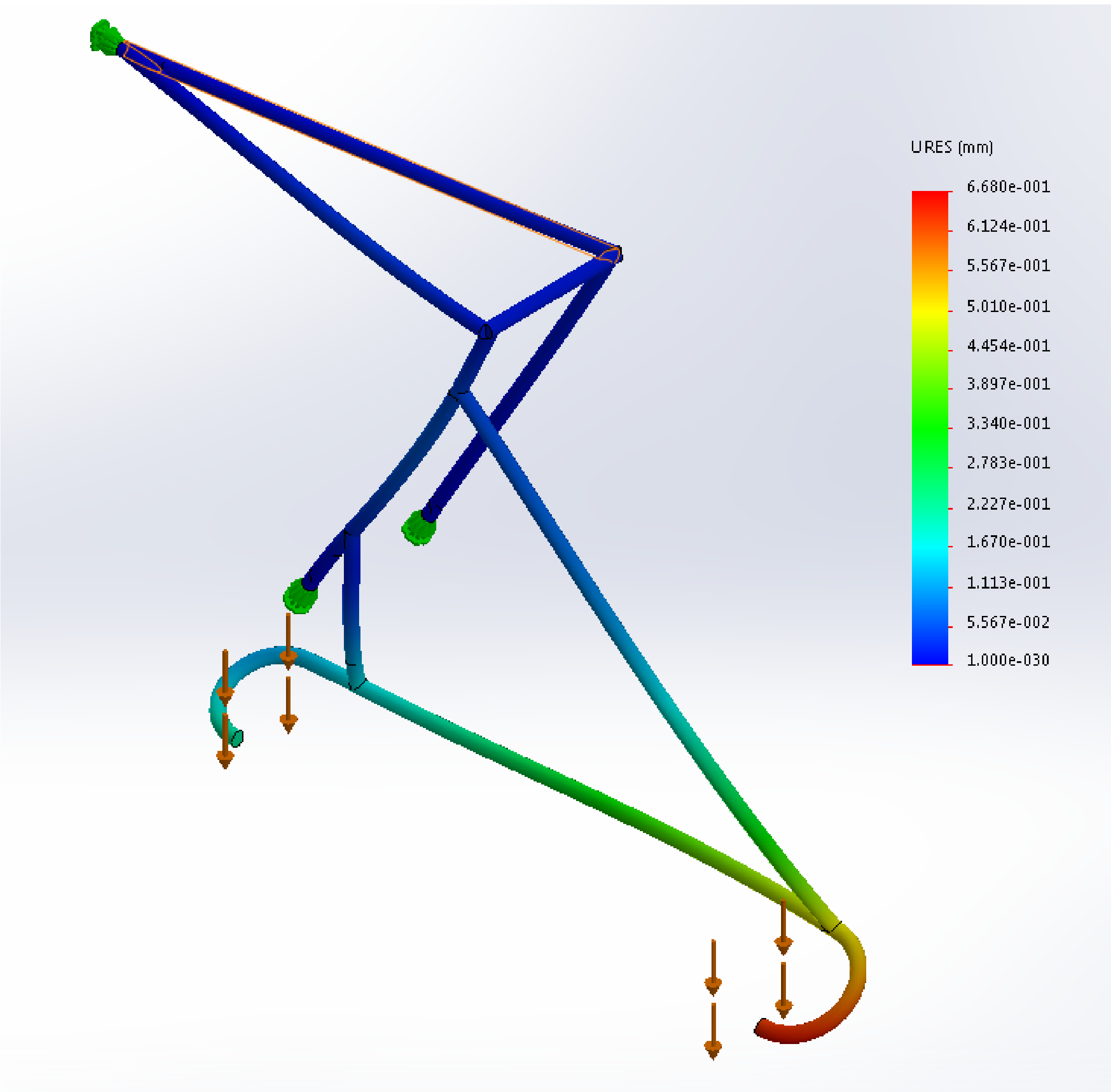


Figure 12: Solidworks drawing of Prototype 3

3.6.3 Prototype 3 Finite Element Analysis

This deflection test was done using a 88 Newton (20 pound) force that was distributed across two points at either end of the bar that holds the towed bike.The largest deflection is 0.66 mm at the rear-most hook. The smallest factor of safety in this simulation is 27.7. This design is very rigid against a downward force and fairly so against a sideways one. The sideways simulation used a 10 pound force applied where the front wheel of the towed bike would be pressing against the device. The largest deflection is 3 mm at the top of the vertical bar. The factor of safety in the sideways simulation is 11.7.

Figure 13: FEA of Prototype 3



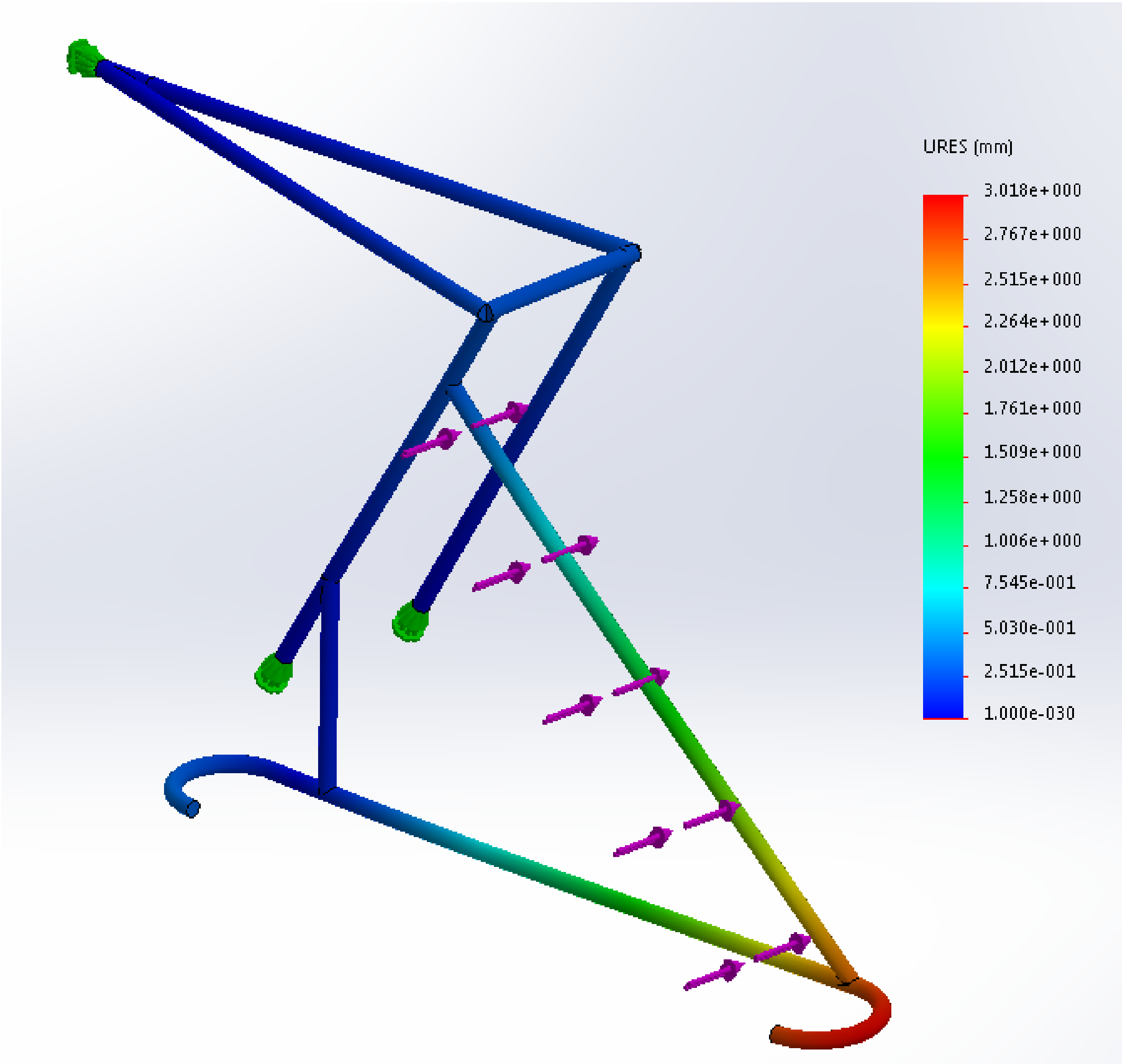


Figure 14: FEA of Prototype 3 (horizontal force)

3.7 Material and Member Considerations

For the purposes of testing prototypes, cold rolled solid steel bar stock was used in two diameters: ½ inch and ⅜ inch. Getting a working prototype was the key goal of this project so different materials were not considered except as potential alternatives in a later section of this report. Also the client works mostly with A36 steel, including welding steel.

Solid bars were used to build the prototypes. Steel tubes or other kinds of structural beams were not considered in this project and could be analyzed in a future project to see if strength requirements are met.

4.0 Methodology

This section covers the steps in the manufacturing process from raw material to a finished bicycle towing device. Specifically, required machines, workstation layout, and processing times are discussed. Additionally, the field testing process for comparing the functionality of the different prototypes are outlined. The Bill of Materials for Prototype 3 can be found in the **Appendix**.

4.1 Manufacturing Process

The following processes and their corresponding machine options are needed to manufacture a bicycle towing device:

Cutting solid steel bar stock to size: This first processing step is needed to cut the large pieces of raw steel bar stock into their appropriate size pieces. This processing step can be accomplished using the following options:

- Horizontal Band Saw
- Cut-Off Saw
- Rebar Cutter

Grinding edges of cut pieces: In order to achieve a minimally sharp edge on the cut metal pieces, a small chamfer should be applied to each edge to achieve safe handling. Additionally, if a cut-off saw is used, the lack of coolant and quick cutting times will burn the edge of the metal creating deformation and extremely sharp edges. Extra grinding time will be needed to produce the desired chamfer. This processing step requires a metal grinding wheel machine. To keep a consistent size and orientation of the chamfer an angled block should be fixed to the base of the grinding wheel.

Metal Bending: The two c-shaped parts that create the slot for the wheel of the towed bicycle need to be bent 180 degrees into this shape. Additionally, the two beams that make up the luggage rack need to be bent approximately 110 degrees. Due to the small radius of these c-pieces, bending these during the prototyping was accomplished with the use of an oxy acetylene torch. A vice for securing the metal piece, a metal pipe for bending the bar stock around, and vice grips were required for this operation. While this process is adequate for prototyping it would have the following difficulties in a manufacturing setting:

- Inconsistent Dimensional Quality: The torch is unlikely to heat the metal in the same way each time, which will affect the overall bend. Also, the human operator adds variation into this process.
- Bottleneck Operation: This was the most timely operation during our prototyping. After a lengthy setup, over a minute was spent to heat each metal piece that needed bending. Often, heating was repeated several times to fully complete the bend.

A tube bending machine with an interchangeable radius, to accomplish large and small bends is recommended for production of this device. Processing time and quality will be significantly improved.

Welding: The welding of the pieces is broken down into four steps each with its own fixture on the welding table. The first two steps create one subassembly, the next step creates another subassembly and the final step welds the two sub assemblies together.

- Step 1: Weld the two long bent bars together where they meet near the seat post. It's important to maintain a 5 ¾ inch gap between the rods where they are bent.
- Step 2: Weld the 5 inch support bar in between the long bent bars to give them lateral support. Careful to weld the support bar above where the tire is supposed to be.
- Step 3: Weld the two connecting rods to the hook-bar, one 5 inch bar and the 19 inch bar. Ensure that the proper angles are maintained to keep the hook bar parallel to the ground and parallel to the lead bike's rear wheel.
- Step 4: Weld the hook-bar assembly to the long bent bar assembly. Again ensure that the proper angles are maintained.

The welding method used for prototype 1 and 3 was arc welding. Prototype 2 was made using TIG welding. This was due to the preferences of the operators that assisted in prototype development. Our client currently uses MIG welding at his facility. The differences between MIG and arc welding are mostly operational and wouldn't affect the strength of the welded joint, therefore MIG would be appropriate for the manufacture of this device.

4.2 Prototype Testing

A field testing plan was created in order to compare the functionality and usability of our three different prototypes. The two main categories of the testing plan are described below:

- Attachability: This is a quantitative data collection of the time it takes to both attach the device to a lead bicycle and secure the trailing bicycle to the device. The quality of the attachment and any variation in the attachment will be observed as well.
- Functionality: This is more of a qualitative observation of the device in action. The performance of each prototype under various bicycle maneuvers will be observed and documented with the aid of a video camera.

Attachability

	Initial State				Prototype 3			
Trial	1	2	3	Ave.	1	2	3	Ave.
Installation (seconds)	97.1	105.3	93.2	98.5	96.2	92.3	82.8	90.4
Secure Bicycle 2 (s)	20.1	17.8	19.6	19.2	23.7	30.5	24.2	26.1

Table 1: Attachability Comparison

Functionality

Category	Initial State	Prototype 3
Low-medium speed, no turning	Significant wobbling	Less wobbling
Medium-high speed, no turning	Stable	Stable
Left turn	Occasionally scrapes the front tire of the towed bike on the ground The towed bike counter-leans in sharper turns	Stable The towed bike counter-leans in sharper turns
Right turn	Stable The towed bike counter-leans in sharper turns	Stable The towed bike counter-leans in sharper turns
Reverse	Unstable Rear bike falls easily	Unstable Rear bike falls easily

Table 2: Functionality Comparison

Prototype 3 outperforms the initial design in lower speeds and in left turns. It provides improved stability in all speeds and more predictable behavior in turns. The initial state design causes the towed bike to tip from side to side when riding at low speed, which is felt as an oscillating force in the handlebar of the lead bike. The oscillation is reduced significantly in Prototype 3 by improving the fastening methods. The hose clamps of the initial design allows for some movement but the attachments at the eyelet holes makes Prototype 3 fit more snug. The initial design doesn't provide enough clearance between the ground and the towed bike's front tire. Prototype 3 has more clearance. Field testing confirmed that the front tire of the towed bike doesn't skid.

5.0 Results and Discussion

This section discusses the specific results of the final prototype, the limitations of its design, possible changes for a future design, and the economics of the design, including the cost to produce it and a suggested retail price.

5.1 Prototype 3 Design Results and Scope Discussion

This design weighs 26.3 pounds. This is 9.9 pounds more than the initial design but this design can be used without the need for a luggage rack. This design is also manufacturable at Mr. Hoadley's facility.

This design is safer than the initial design, which had a factor of safety of 3.8 for a downward force of 20 pounds on the hook-bar. The smallest factor of safety in this design is 27.7 for a downward force of 20 pounds on the hook-bar and 11.7 for a sideways force of 10 pounds on the long support bar.

There are three points where the device is fastened to the bike. One on the seatpost where the device is secured with a P-clamp, a bolt, and a wingnut. The other two points are at the eyelets on the bike frame near the rear hub. These are secured with two small bolts that screw into the threads in the eyelets. For testing purposes an Allen wrench was used to tighten the two M5 bolts. However, M5 wing head bolts could be used. Therefore this design has a toolless assembly.

This prototype is designed to fit our test bike. Theoretically the design can be adjusted to fit any diamond frame bike and some other frames, but because this prototype uses half inch steel bar it's difficult to flex the bar to fit the slightly different dimensions of different manufacturers. What most luggage rack manufacturers do is design the connecting rods (or the entire rack) to be made from quarter inch steel or aluminum so the user can bend the rods to fit his specific bike.

5.2 Limitations of the Design

This design has a number of issues:

- Heavy
- Makes it difficult to use a luggage rack at the same time
- Only fits bikes similar to the test bike

5.3 Possible Design Changes

To address the issues listed above some changes could be made to the design. Further testing would be necessary.

The device could be made from solid half inch aluminum for a 66% reduction in weight.. Using solid 3/8ths inch aluminum would have a 74% reduction in weight and solid 3/8ths inch steel would have a 25% reduction in weight. FEA analyses would have to be performed to see if there are any significant changes to the deflection of the device under load and the factor of safety. One consideration for aluminum is that it doesn't perfectly elastically deform and will accrue stress over time; this should be considered for failure and reliability tests.

For stability reasons this design attaches on both sides of the rear wheel. This makes it impossible to attach a luggage rack in the same place. As a work around a consumer could use a luggage rack that is only connected only to the seat post, but these racks have low maximum weight limits. With a couple crossbars for support this design could be modified to act as a luggage rack. FEA analyses would need to be done to determine how an additional load affects the performance if the device and what the maximum recommended load is given a predetermined factor of safety.

The biggest change that would improve this design would make it more adjustable. Having thinner, more flexible rods that are attached to a rigid frame would allow this device to attach to bikes given a variable axle width and variable distance to the seat post. Thinner rods sacrifice strength for flexibility, FEA analyses would help determine if thinner rods don't sacrifice stability through a rigid frame.

5.4 Economic Analysis

This section discusses all of the attributing costs to the manufacture of this product and suggests a final retail price.

5.4.1 Material and Packaging Costs

This design used 117.9 inches of solid half inch steel bar stock. Due to the manufacturing process 12 feet of steel is needed for each device. A supplier in Santa Maria, B&B Steel, delivers 20 foot steel bar stock to San Luis Obispo for $18.50. With that price each device would cost $11.10 just for the steel.

The auxiliary materials are a ¼ inch x 1 ¼ inch hex bolt, a ¼ inch wing nut, a 1 inch P-clamp, two M5 wing head bolts, and a 24” reusable gear tie.

Item	**Cost per item** (bulk prices, in dollars)
hex bolt	0.26
wing nut	0.16
P-clamp	1.56

M5 wing head bolts	0.79
gear tie	3.25
	Sum = 6.81

Table 3: Cost of fasteners

The total cost of the materials is $17.91 per unit.
The cost of packaging approximately $3 per cardboard box and $3 for bubble wrap per unit.

5.4.2 Labor and Storage Costs and Batch Size Analysis

The cost of labor is assumed to be the median salary for a welding technician in the United States: $17.76 per hour. WIP storage costs average roughly $1 per unit of finished good. At this rate the appropriate batch size is calculated to reduce total cost per unit.

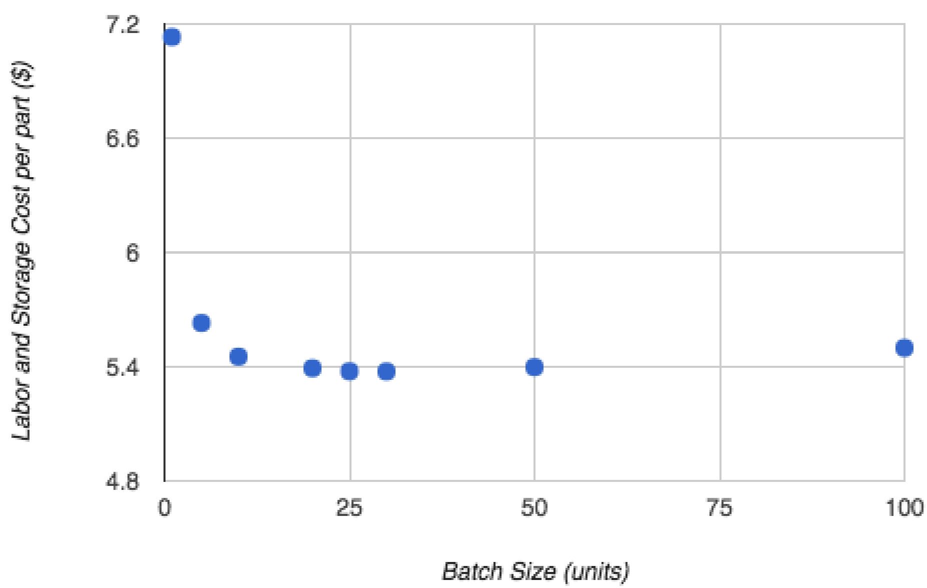


Figure 15: Batch Size Analysis

It is assumed that the operators are working one 8 hour shift per day, and there is two fifteen minute breaks and one half hour break resulting in 7 hours of work for an 8 hour shift. Batch times are the setup times for the operation plus the run time for the operation multiplied by the number of units in the batch (**Routing Sheet** found in the **Appendix**). The most appropriate batch size is 30 units per batch.

The final product can be stored in a box that is 1’ by 2’ by 3’. This box can be stacked on shelves up to three boxes high. It’s footprint is 2 square feet. This results in an average of 1.5 units stored per square foot. At a rate of $1.5 per unit per sq. ft. per month the cost of final goods storage is roughly $1.

5.4.3 Equipment Costs

The investment required to purchase the necessary equipment to create a manufacturing facility are listed below:

Workstation	**Equipment**	**Investment**
Welding	MIG Machine + Welding Kit	$1,000
	Welding Table + Fixtures	$450
	Gloves	$30
	Mask	$50
	Curtain	$40
Cold Bending	Tube Bender	$3,125
Grinding	Metal Disk Grinder	$1,200
Cutting	Rebar Cutter	$180
	Lumber Rack	$60
	Roller Stands	$50
Pressing	Hydraulic Press	$300
Drilling	Drill Press	$200
Packaging	Table	$50
Finished Goods Storage	Shelves	$1,000
Raw Material Storage	Wall Rack	$100
Transportation	Cart	$100
	Total	**$7,935**

Table 4: Equipment Costs

One of the necessary steps in the manufacture of this product is powder coating. An analysis is performed in the next section to judge the merit of outsourcing this step or performing it in-house.
This is the cost of the powder coating equipment.

Powder Coating	Spray Gun	$110
	Spray Booth	$4,400
	Curing Oven	$16,500
	Sand Blast Cabinet	$4,400
	Total	**$25,410**

Table 5: Powder Coating Equipment Costs

5.4.4 Financial Analysis and Powder Coating Outsourcing Justification

This a complete financial analysis that assumes an annual sales volume of 5000 units and a retail price of $65.

	Buy	**Make**
Yearly Volume	5,000.00	5,000.00
Selling Price	$65.00	$65.00
Annual Revenue	$325,000.00	$325,000.00
Time per part (hr)	0.26	0.96
# of employees	1.00	2.00
Labor cost per hour	$17.76	$17.76
Labor Cost per Part	$5.28	$38.97
Material Cost per Part	$17.91	$16.41
Powder Coating	$25.00	$0.25
Packaging	$6.00	$6.00
COGS	$270,941.36	$308,162.72
Gross Margin	$54,058.64	$16,837.28
Total Sq. Footage	1,550.00	2,350.00
Monthly cost/sq. ft	$1.50	$1.50
Annual Lease Cost	$27,900.00	$42,300.00
Operating Material Cost	$2,000.00	$2,000.00
Utilities	$3,000.00	$7,500.00
Operating Cost	$32,900.00	$51,800.00
Investment	$7,935.00	$33,345.00
Machine Life	5	5
Depreciation	$1,587.00	$6,669.00
Taxable Income	$19,571.64	-$41,631.72
Tax Rate	0.4	0.4
Taxes	$7,828.66	-$16,652.69
Net Income	$11,742.98	-$24,979.03
Annual Cash Flow	$13,329.98	-$18,310.03

Table 6: Powder Coating Make vs. Buy

According to the chart above, choosing to outsource the powder coating operation is an economically justified decision. The annual cash flow would be approximately $13,000 to outsource the operation compared to a cash flow of approximately -$18,000. Purchasing additional equipment and increasing the utilities, lease cost, and labor cost to powder coat the products is not financially beneficial. The drastic financial difference in these two options is likely due to the unutilization of all the powder coating equipment and space.

The financial analysis above assumes an annual volume of 5000 and a retail price of $65. Below is a chart showing how the annual cash flow changes with changes in sales volume and retail price.

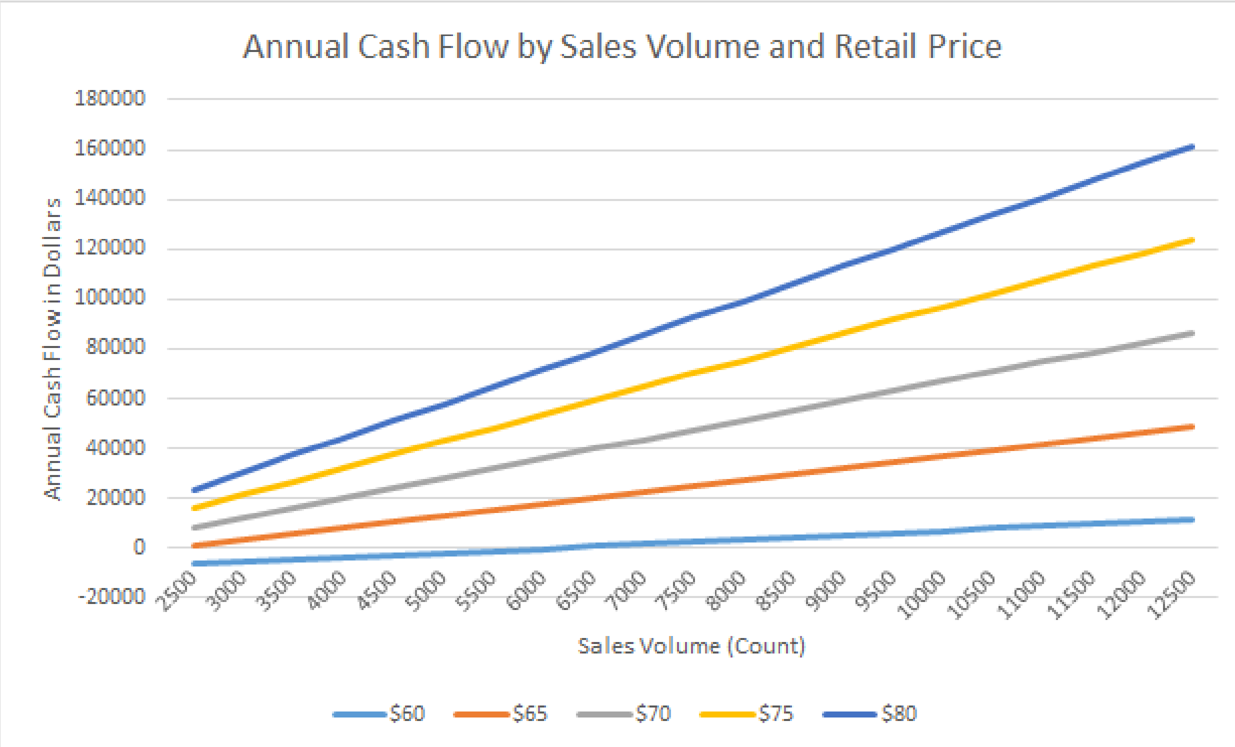


Figure 16: Annual Cash Flow by Sales Volume and Retail Price

While raising the retail price significantly increases annual profit, it may be hard to meet the high sales volumes. Since this product doesn't really exist in the market, it is hard to guess the potential market size. "Similar" products (rear luggage racks) sell for anywhere from $40 to $75 dollars. With this in mind the suggested retail price is $65.

6.0 Conclusions

The process of improving the initial prototype consisted of designing, testing, and building 3 different prototypes. Each was built to solve problems associated with its predecessor. The initial design only worked on bikes with luggage racks, it was heavier than desired, and it required tools for attachment. Prototype 1 is designed to attach to the seatpost instead of the luggage rack. It was built in ⅜ in. diameter steel rods instead of ½ in. It attaches with without tools by using P-clamps and wing-nuts. Prototype 1 attached very well to the leading bike, but it failed to keep the rear bike stable. When the towing bike makes a turn the towed bike folds and falls over very easily. Prototype 2 is designed to fix these problems. It is a similar design to the initial state but instead of attaching to a luggage rack it attaches to the seatpost. This design is also built out of ⅜ in. diameter steel rods.

Prototype 2 fits the towing bike well but when the towed bike is attached the device rubs against the rear wheel of the towing bike. It only works when a luggage rack is used, which means it's no better than the initial state. The design of prototype 3 was made to fix the rigidity issues of the previous prototypes. It is attached by both sides of the rear axle with bolts into threaded eyelets, and to the seatpost. None of these fasteners require tools for attachment. It's built out of ½ in. diameter steel rods. It works without a luggage rack and handles better than the initial state design. When tying the result back to the problem statement, the project succeeded in creating an easily attachable/detachable and commercially viable design that is manufacturable at the client's facility. It is not adjustable but it's designed to fit most diamond frame bicycles. The suggested retail price is $65.

Our recommendation is for our client to move forward with this design (as a stable working model) and improve upon its adjustability and weight, considering different materials or member structure. The environmental impact of this product is the reduced need for a car when transporting bikes, which reduces consumption of fossil fuels. The social impact is creating a more bike friendly community.

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Appendix

Routing Sheet

Operation		Input Part No.	Output Part No.	Quantity per part	Machine/Workstation	Setup Time	Run Time per part (sec)
No.	**Description**						
		B1	L5	1	Rebar Cutter	10	10
		B1	R5	1		10	10
		B1	S2	1		10	10
		B1	D1	1		10	10
		B1	H1	2		10	20
	Deburr All Cut Parts	N/A	N/A	N/A	Metal Disk Grinder	0	120
		L5	L4	1	Cold Bending Machine	10	80
		R5	R4	1		10	80
		S2	S1	1		10	160
		L4	L3	1	Press	5	20
		R4	R3	1	Press	5	40
		L3	L2	1	Drill Press	40	60
		R3	R2	1		15	60
		L2	L1	1		40	60
		R2	R1	1	Metal Disk Grinder	15	30
		H1	V1	1		15	30
		L1, R1, H1	F1	1	Welding	60	20
		S1, V1	C1	1		20	10
		F1, C1, D1	A2	1		40	15
		A2	A1	1	Powder Coating	N/A	N/A
	Package Bike Tow &	N/A	N/A	1	Packaging	0	150

	Fasteners						
					1 operator	335	845

Bill of Materials

Level	Part No.	Part Name	Qty/ Unit	Mfg. or Purchased
0	A1	Bike Tow	1	M
1	A2	Bike Tow Uncoated	1	M
2	F1	Rack Frame	1	M
3	L1	L Complete	1	M
4	L2	L Drilled 1	1	M
5	L3	L Flattened	1	M
6	L4	L Bent	1	M
7	L5	L Cut	1 @ 35"	M
8	B1	Raw Steel Barstock	1	P
3	R1	R Complete	1	M
4	R2	R Ungrinded	1	M
5	R3	R Undrilled	1	M
6	R4	R Bent	1	M
7	R5	R Cut	1 @ 33"	M
8	B1	Raw Steel Barstock	1	M
3	H1	Horiz. Join	1 @ 5"	M
4	B1	Raw Steel Barstock	1	P
2	C1	Addition Slot	1	M
3	S1	Full Slot	1	M
4	S2	Slot Cut	1	M
5	B1	Raw Steel Barstock	1	P
3	V1	Vert. Join	1	M
4	H1	Horiz. Join	1 @ 5"	M
5	B1	Raw Steel Barstock	1	P
2	D1	Diag. Join	1 @ 20"	M
3	B1	Raw Steel Barstock	1	P
1	P1	1" P Clamp	1	P
1	P2	.25" Wing Nut	1	P
1	P3	.25" x 1.25" Hex Bolt	1	P
1	P4	.19" Wing Head Bolt	2	P